High energy phenomena in young stars

Eric Feigelson (Penn State)

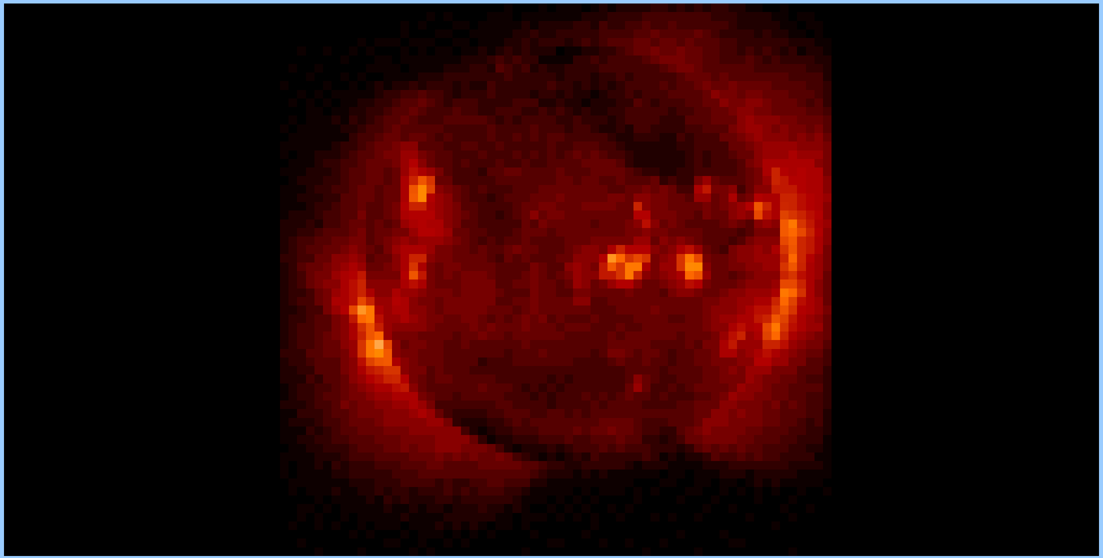
1. Background: Magnetic activity in PMS stars

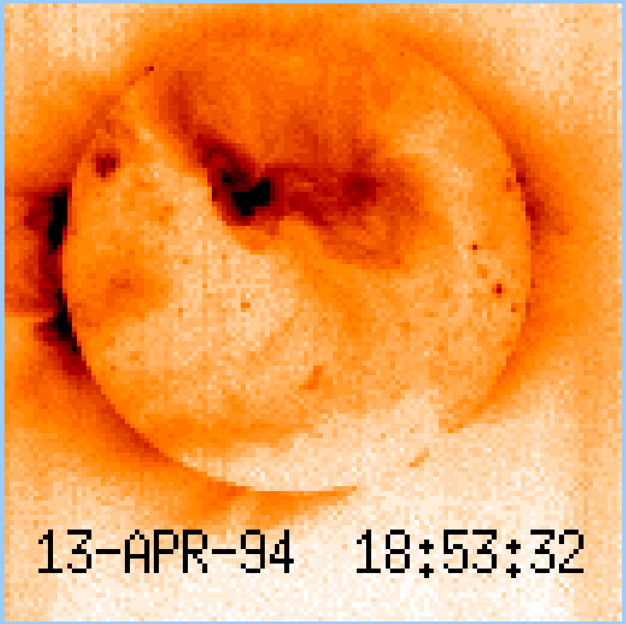
2. A first look at the Chandra Orion Ultradeep Project & other recent results

3. A puzzle: No activity/rotation relation in PMS stars

4. X-rays, circumstellar disks & planet formation

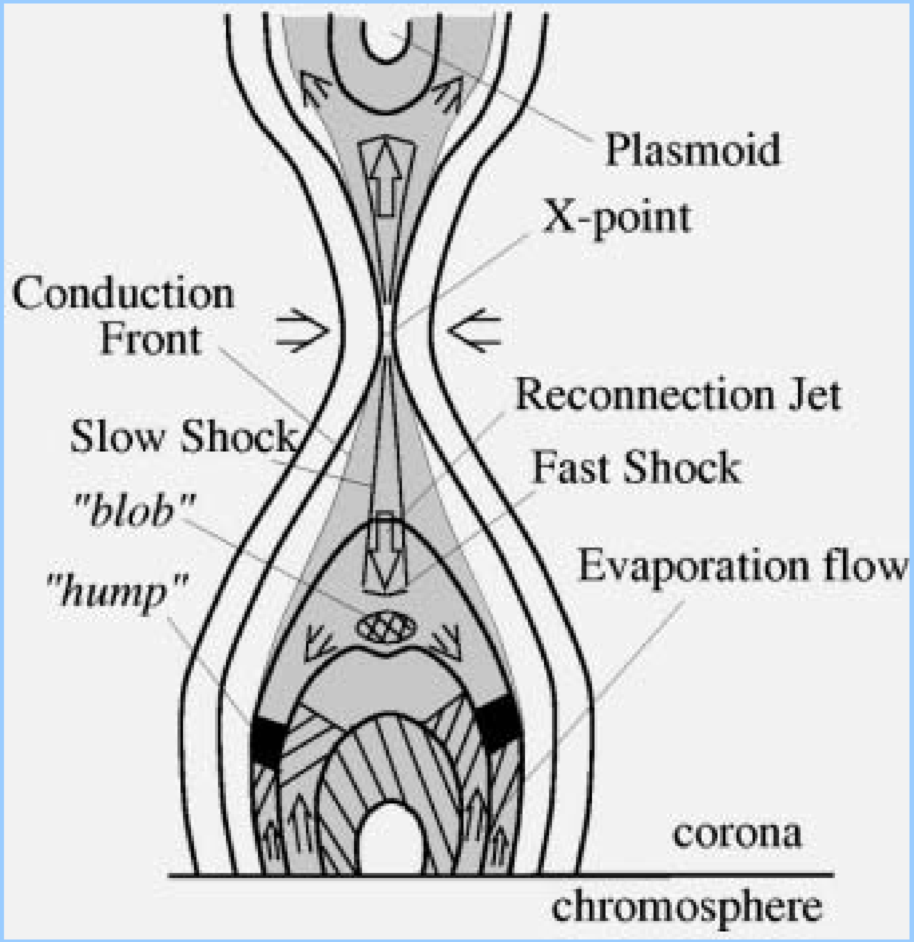
Stellar X-rays arise from magnetic reconnection events and thus trace the MHD of stellar interiors and environments

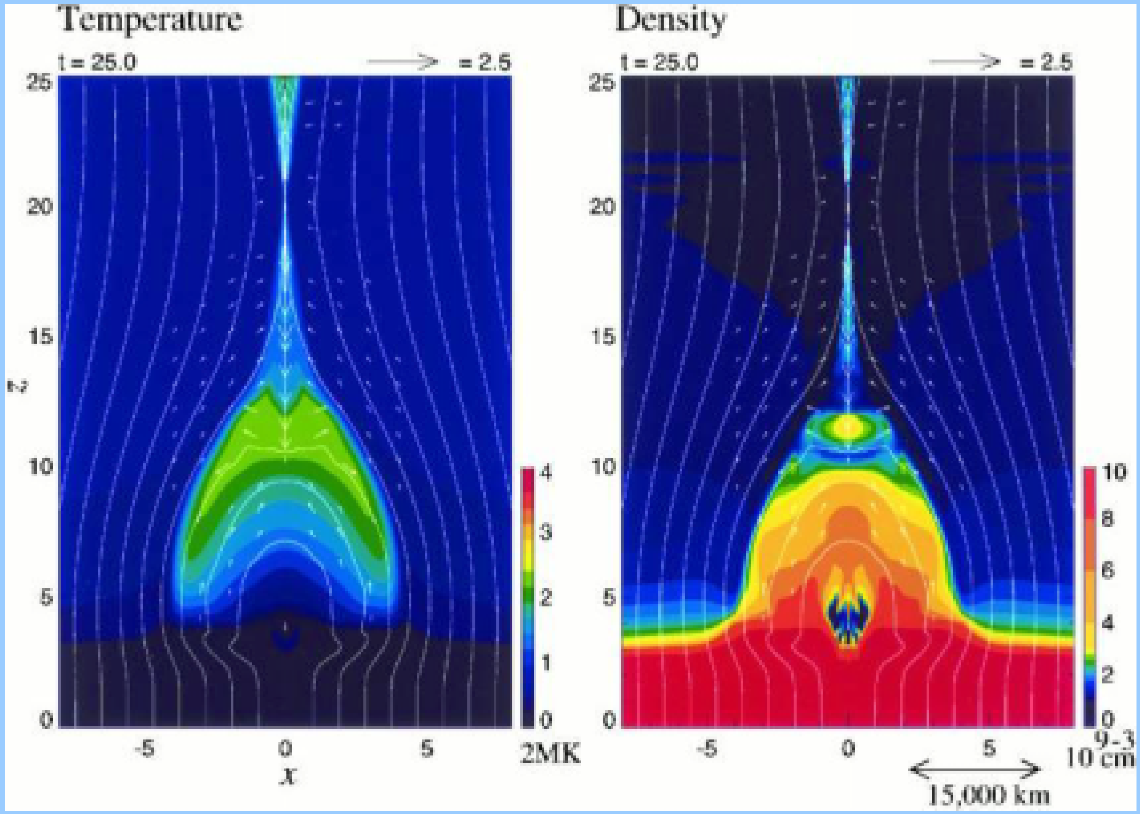




Yohkoh movies of the X-ray Sun: several weeks (left) and several hours (right)

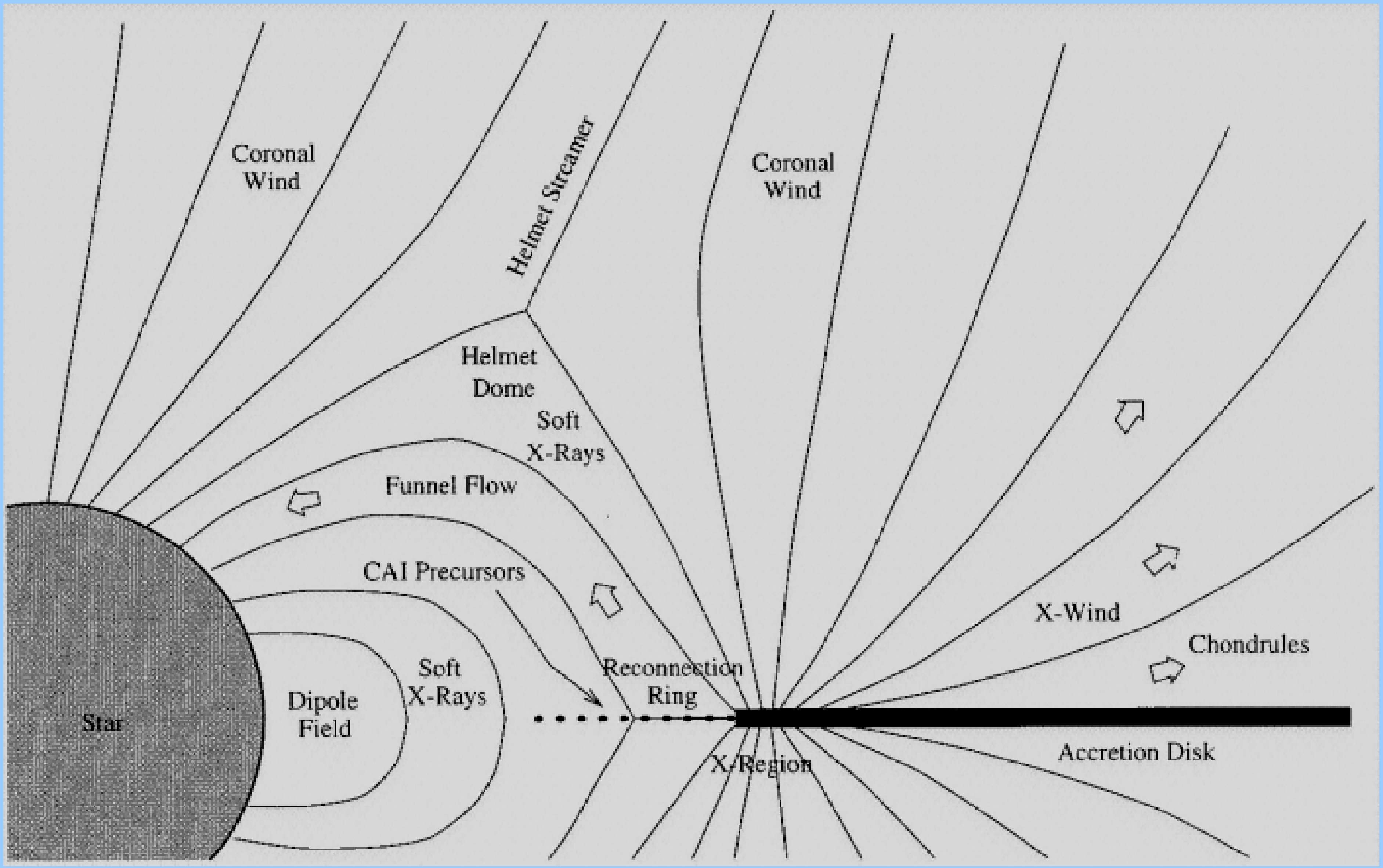
Model of an X-ray solar flare





Yokohama & Shibata 1998

A contemporary model for protostars & T Tauri stars



Shu et al. 1997, 2001

Why study activity in pre-main sequence stars?

- **Ordinary solar-type stars exhibit their highest levels of magnetic activity during their PMS phases**

  $<log\ L_X>$ = 30.2 erg/s for a well-defined sample of PMS solar analogs, compared to $<log\ L_X>$~27 erg/s for the contemporary active Sun and ~28.5 erg/s for the most powerful recent flares

  Feigelson et al 2002a, Peres et al 2000

- **Large samples of stars can be studied in one field**

- **Energetic radiation from PMS flares can affect the circumstellar environment**

The Astrophysical Journal, 178:281–308, 1972 December 1

THE *UHURU* CATALOG OF X-RAY SOURCES

R. Giacconi, S. Murray, H. Gursky, E. Kellogg,
E. Schreier, and H. Tananbaum
American Science & Engineering, Cambridge, Massachusetts
Received 1972 May 4

ABSTRACT

A catalog of X-ray sources observed with the *Uhuru* satellite is presented. About 70 days of data have been analyzed for this catalog resulting in 125 sources. Approximately two-thirds of the sources are located within $\pm 20°$ of the galactic plane. Some of the sources at higher galactic latitudes are identified with known extragalactic objects. Most of the strong sources near the galactic plane are found to be variable.

	Location of Maximum Probability Density		Error Region for 90 Percent Confidence					Intensity		Comments and General Remarks	
Source Name (1)	α (1950) δ (1950) (2a)	l^{II} b^{II} (2b)	1 α δ (3a)	2 α δ (3b)	3 α δ (3c)	4 α δ (3d)	Area (square degrees) (3e)	Average or Maximum (4a)	Max. Obs./ Min. Obs. (4b)	Counterparts (5a)	Previous X-Ray (5b)
2U 0521−72 . . .	5 21 36 −72 1 12 80.40 −72.02	283.10 −32.66	5 21 41 −71 56 24 80.42 −71.94	5 20 14 −72 3 0 80.06 −72.05	5 21 14 −72 6 0 80.31 −72.10	5 22 38 −72 0 36 80.66 −72.01	0.014	14.9 ± 1.0		In LMC	LMC X-2 (7)
2U 0525−38 . . .	5 25 7 −38 0 0 81.28 −38.00	242.53 −32.26	5 28 0 −35 49 12 82.00 −35.82	5 7 50 −38 43 12 76.96 −38.72	5 18 34 −40 0 0 79.64 −40.00	5 39 50 −37 21 36 84.96 −37.36	12.000	2.0 ± 0.3			
2U 0525−06 . . .	5 25 12 −6 7 12 81.30 −6.12	208.75 −21.39	5 42 48 −4 0 0 85.7 −4.0	5 14 48 −7 6 0 78.7 −7.1	5 15 36 −7 24 0 78.9 −7.4	5 44 24 −4 12 0 86.1 −4.2	2.700	3.8 ± 0.4		M42? Orion radio nebula?	
2U 0531+22 . . .	5 31 24 22 0 0 82.85 22.00	184.53 −5.80	5 31 30 +22 2 6 82.876 22.035	5 31 16 22 2 6 82.815 22.035	5 31 16 21 57 54 82.815 21.965	5 31 30 21 57 54 82.876 21.965	0.004	947 ± 21*		Crab nebula NP 0531?	Tau X-1 (1) Crab (2) Tau 1 (3)

Chandra studies of young low mass stars

Ophiuchus: *Imanishi et al 2001ab, 2002, 2003; Gagne et al 2003*

Tau-Aur: *Bally et al 2003; Stelzer et al 2003*

Perseus: *Preibisch & Zinnecker 2001, 2002; Getman et al 2002*

Orion: *Garmire et al 2000; Schulz et al 2001; Pravdo et al 2001; Tsuboi et al 2001; Feigelson et al 2002ab, 2003; Flaccomio et al 2002, 2003; Tsujimoto et al 2002; Skinner et al 2003; Grosso et al 2003*

Older dispersed young stars:

- **TW Hya** *Kastner et al 2002, Tsuboi et al 2003*
- **κ Cha** *Feigelson et al 2003*
- **B stars** *Stelzer et al 2003*

D~1-2 kpc star forming regions:

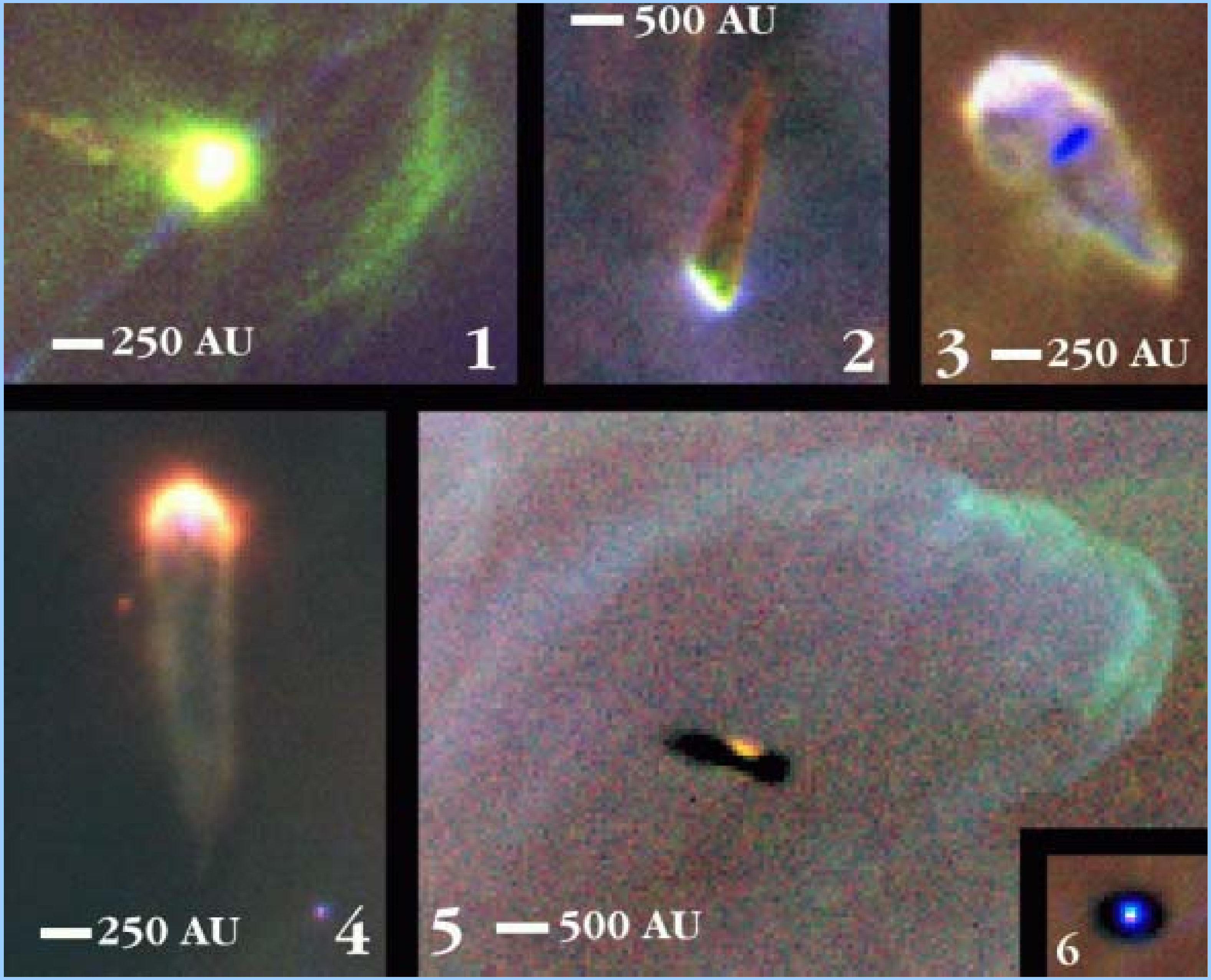
- **Carina Neb** *Evans et al 2003*
- **Mon R2** *Kohno et al 2002 Nakajima et al 2003*
- **Cep OB3** *Pozzo et al 2003*
- **IRAS 19410+2336** *Beuther et al 2002*

+ many studies of massive star formation regions

The Orion Nebula field

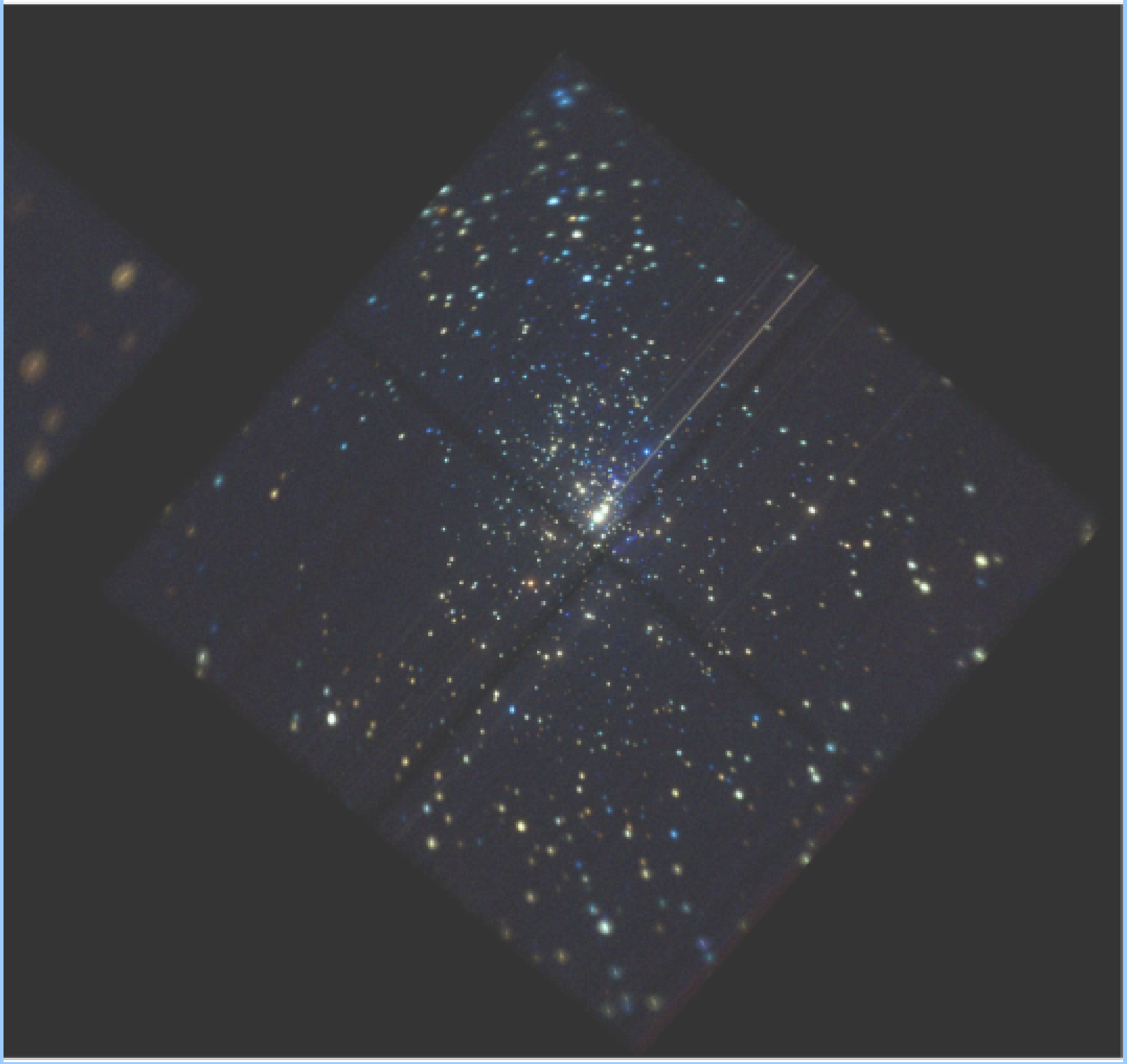
Orion Nebula Cluster (ONC) illuminating the HII region M42

Circumstellar disks around Orion PMS stars



HST: Bally/O'Dell

Chandra Orion Ultradeep Project



COUP: Chandra Orion Ultradeep Project

Principal Investigator: Eric Feigelson (Penn State)

Group leaders:

Data reduction & catalog	**Kosta Getman (Penn State)****
X-ray spectra & variability	**Rick Harnden (SAO)**
Optical variability	**Keivan Stassun (Wisc)**
Origin of T Tauri X-rays	**Thomas Preibisch (MPIfR)**
Embedded stars	**Nicolas Grosso (Grenoble)**
Brown dwarfs	**Mark McCaughrean (AIP)**
Massive stars	**Thierry Montmerle (Grenoble)**
Effects of X-rays	**Francesco Palla (Arcetri)**

Participating COUP scientists:

John Bally	**Patrick Broos**	**Paola Caselli**	**Francesco Damiani**
Fabio Favata	**Ettore Flaccomio**	**Gordon Garmire**	**Alfred Glassgold**
William Herbst	**Lynne Hillenbrand**	**Joel Kastner**	**Charles Lada**
Andrea Lorenzani	**Gwendolyn Meeus**	**Giusi Micela**	**Thierry Morel**
Norbert Schulz	**Salvotore Sciortino**	**Hsieh Shang**	**Beate Stelzer**
Leisa Townsley	**Yohkoh Tsuboi**	**Masahiro Tsujimoto**	**Maureen van den Berg**
Scott Wolk	**Hans Zinnecker**		

**** see data methods posters by Broos, Getman & Tsujimoto**

COUP is constructing an atlas of ~1632 sources

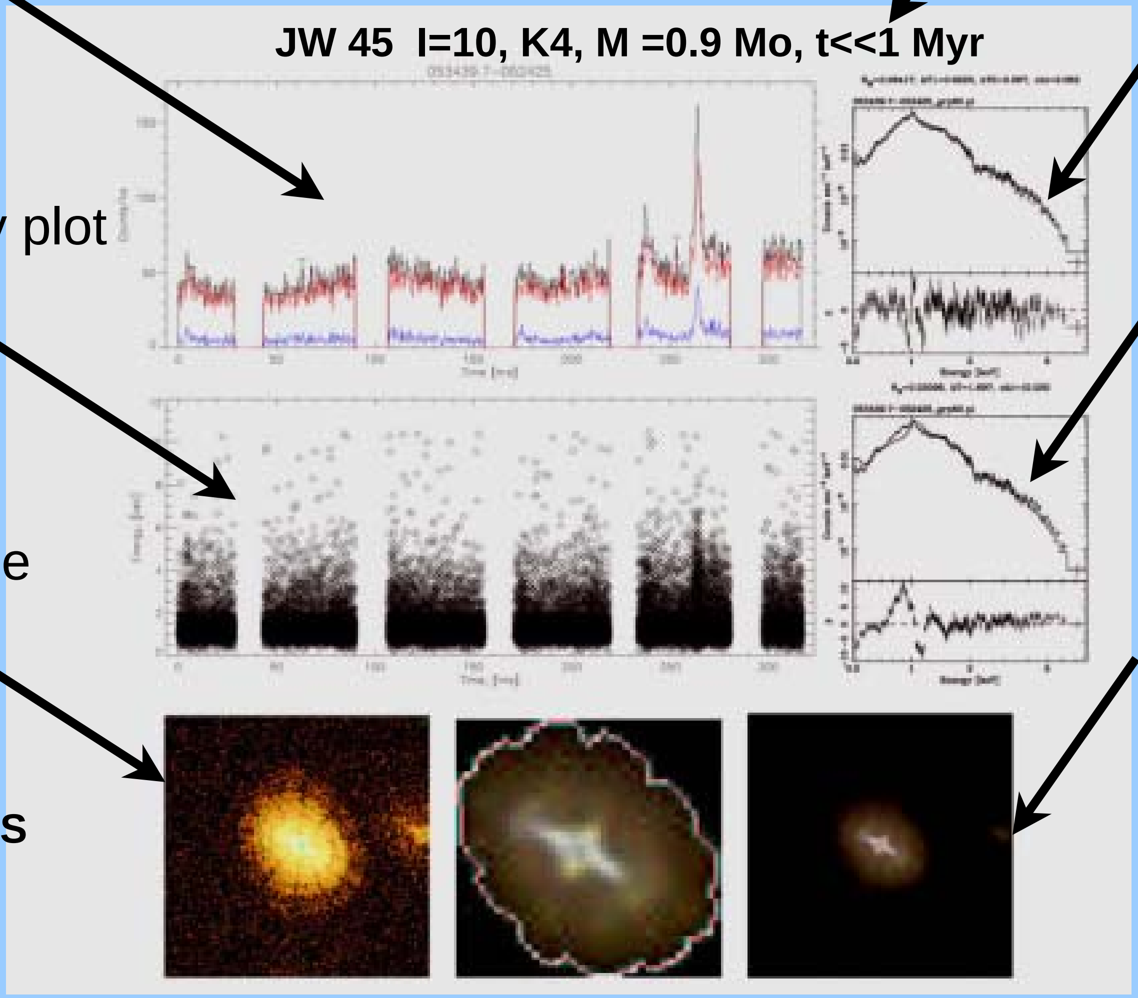
Optical/IR counterpart

Light curve: 9.8 days exposure spanning 13.2 days

0.5-8 keV spectrum with 2-T plasma model

Time-energy plot

1-T plasma model



50”x50” image

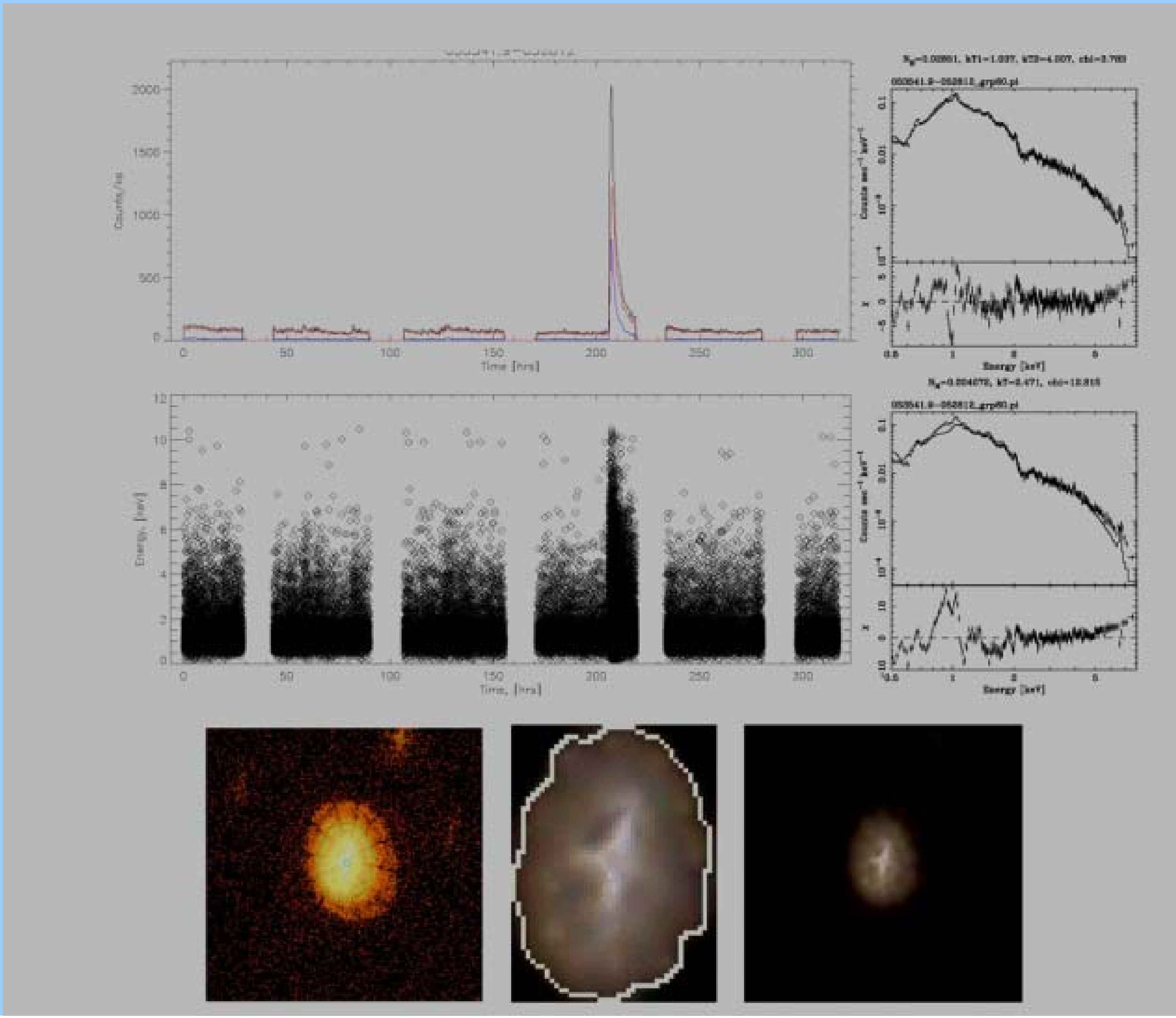
Polygonal extraction area

Small o = 2MASS
Small + = VLT

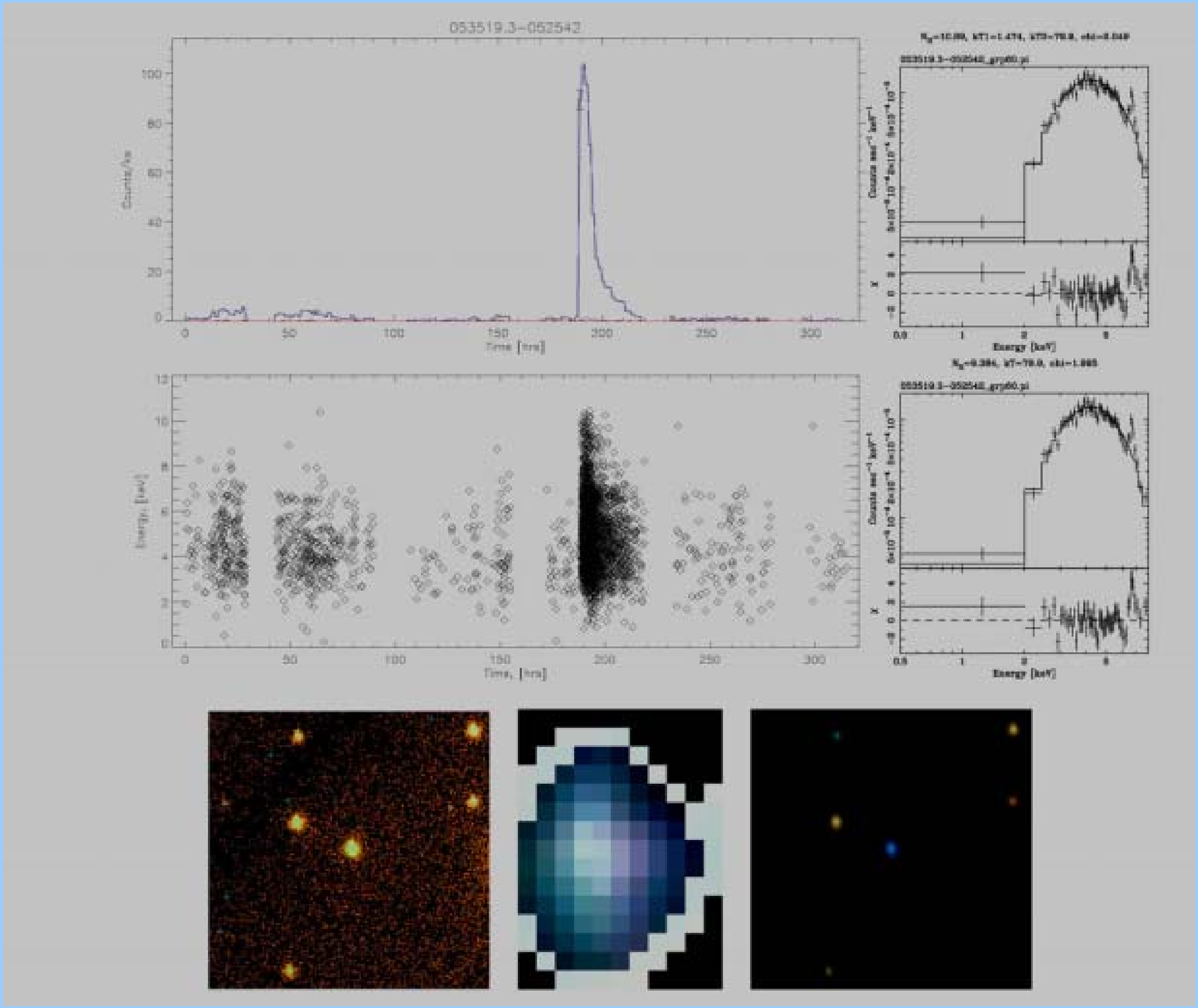
Smoothed & energy coded color image

A large flare with abundance anomalies

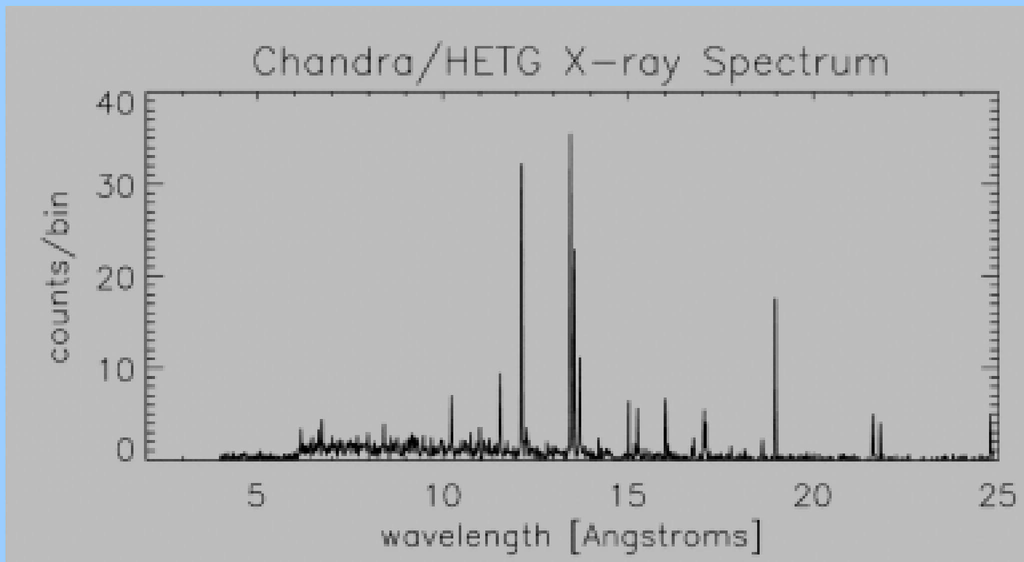
JW 959, K0, M=2 $M_{\odot}$, t=1 Myr



A very hot flare with iron excess?
MLLA, K=10



The unusual properties of the nearest & brightest classical T Tauri star: TW Hya



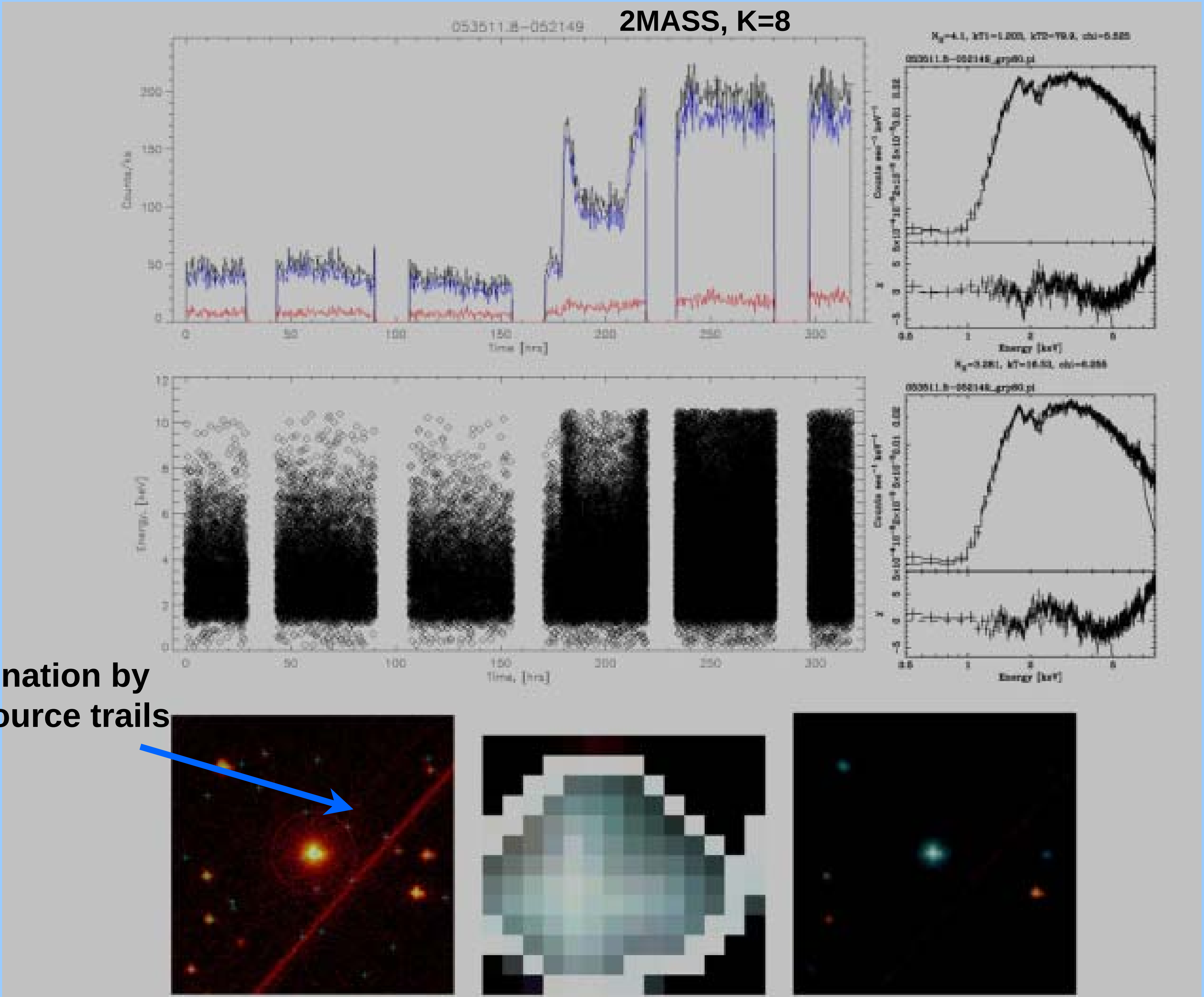
- **Main component is soft: kT~0.3 keV**
- **Abundance anomalies: O, Ne, Fe ~ 0.3 solar**
- **Density high: Ne IX triplet gives log n~12.8**
- **Variability: rise < 2ks, decay ~ 15 ks**

Soft kT & density suggests accretion origin
Abund & var suggest flare origin

Chandra HETGS   Kastner et al. 2002

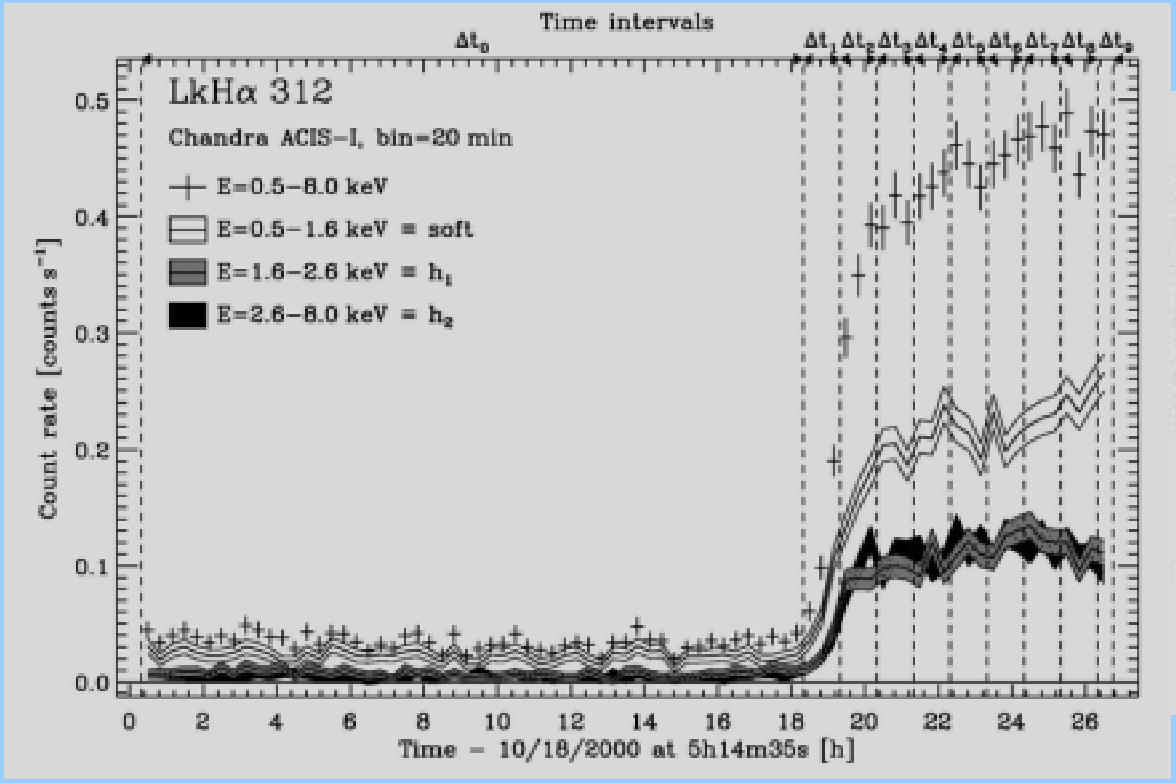
Some flares have extremely long rise & cooling timescales

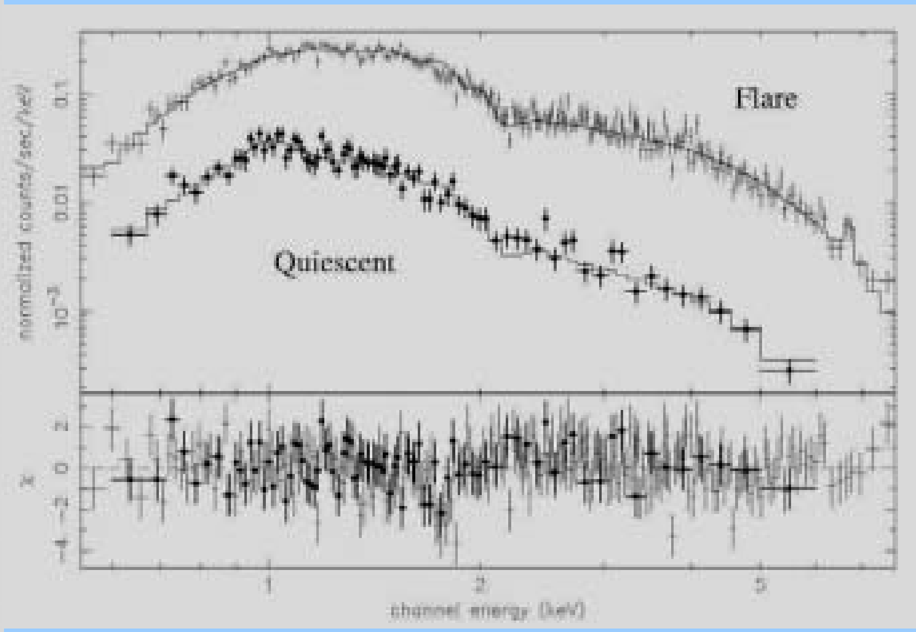
2MASS, K=8



Contamination by bright source trails

An unusually long & powerful flare in weak-lined T Tauri LkHζ 312





Host star: SpTy=M0 Mass~0.7 M_o Age~5 Myr no IR disk or accretion

log L_x rises from 30.8 to 32.1 erg/s

kT rises from 1+3 keV to 6 keV and falls to 4 keV

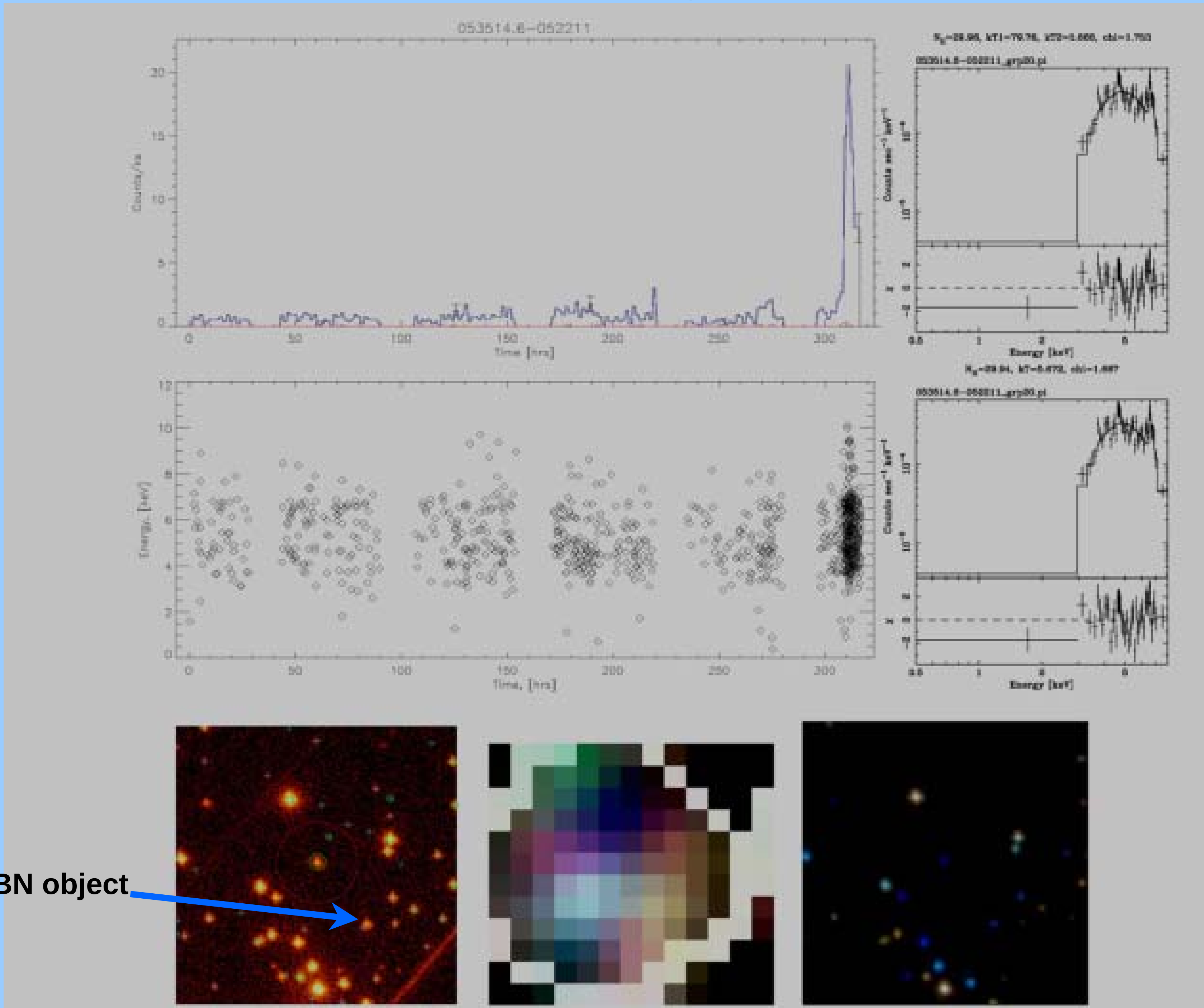
No abundance anomalies

Flare loop models give size h <~ 0.5 R*

Grosso et al. 2003

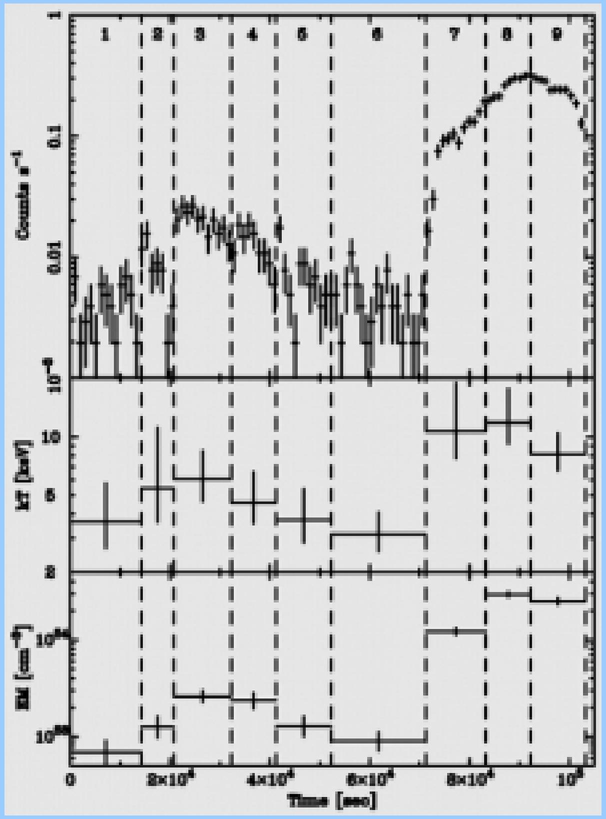
An extremely absorbed source: N_H=3x10^{23} cm^{-2} or A_V ~ 200

New source in BN/KL region



BN object

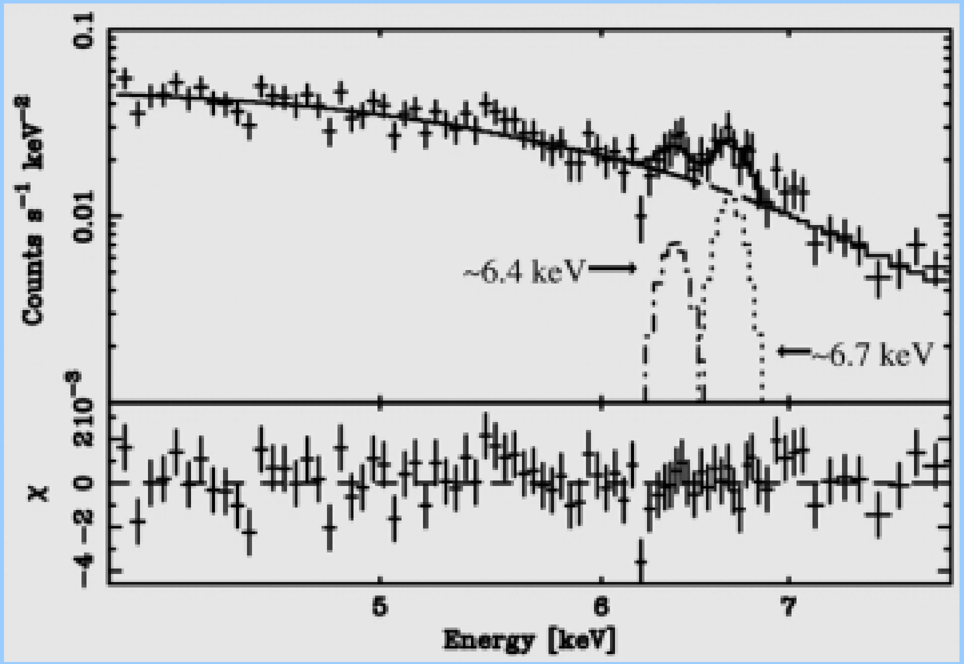
Flaring Class I protostars in Ophiuchus



YLW 16A
29.5 < log L_X < 32.0 erg/s

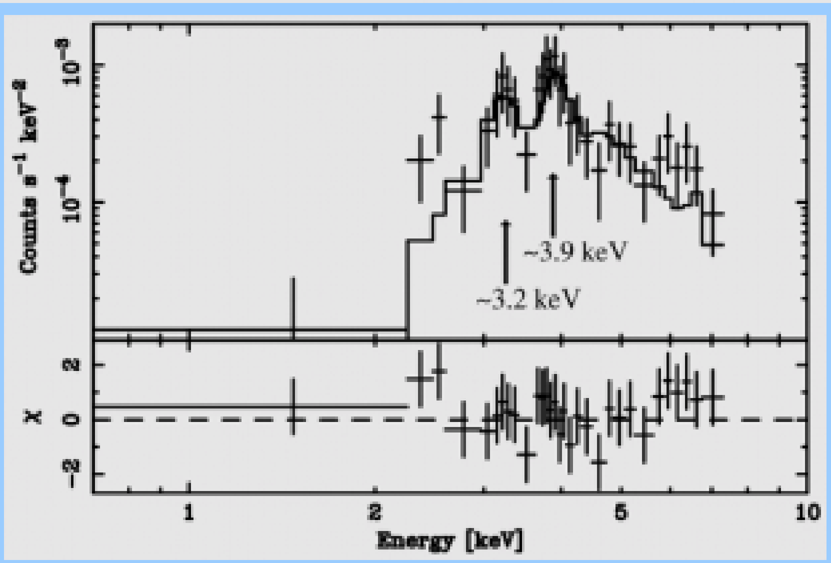
YLW 16A

6.4 & 6.7 keV
Fe lines



WL 22

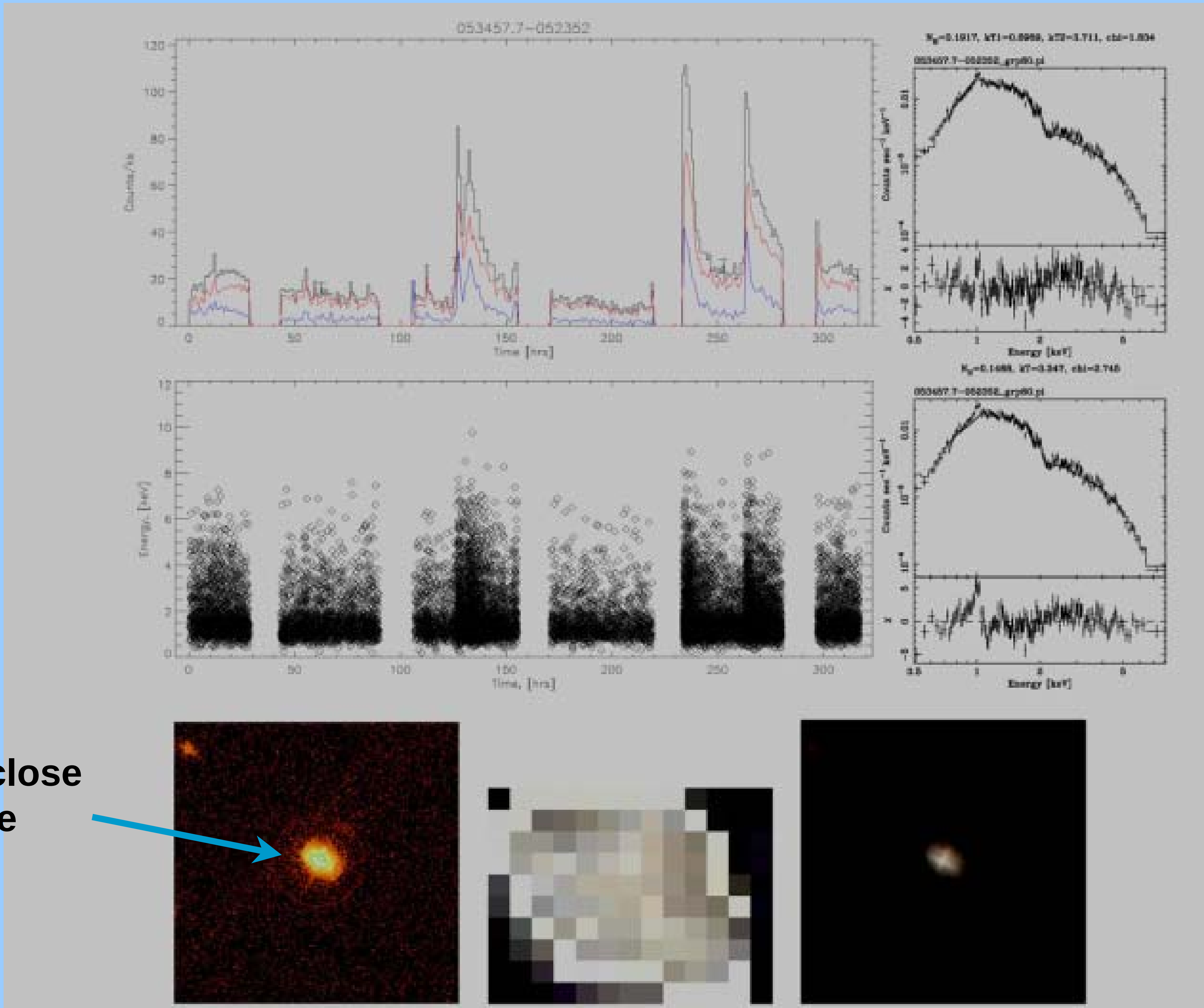
Ca & Ar
excess



Imanishi et al. 2001

Multiple flares during 13 days are common

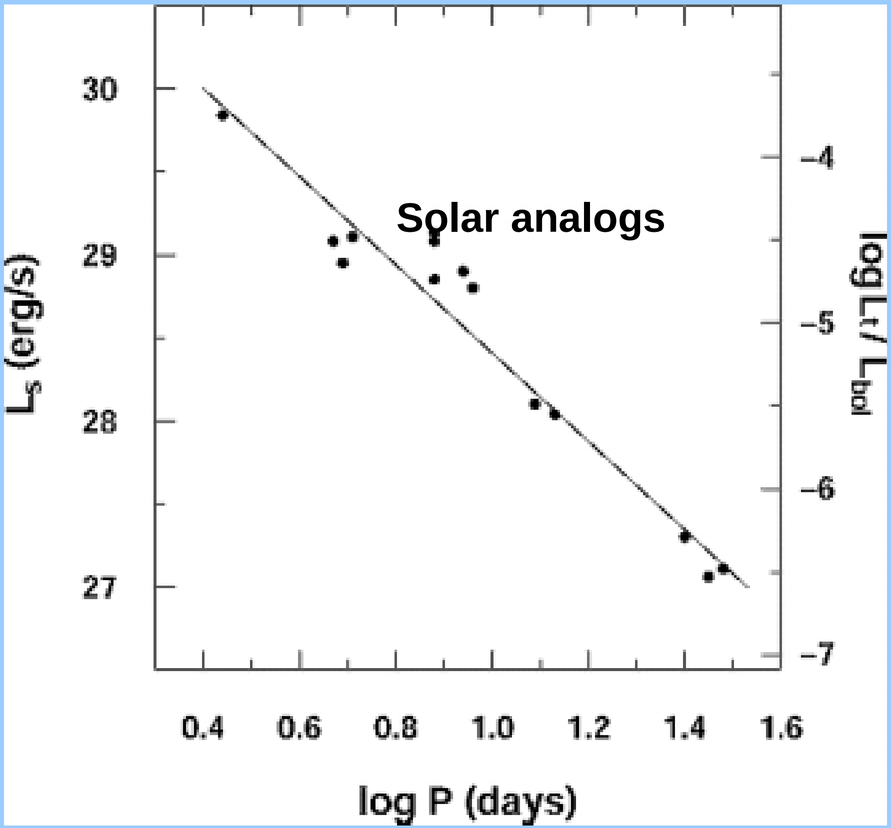
2MASS, K=9



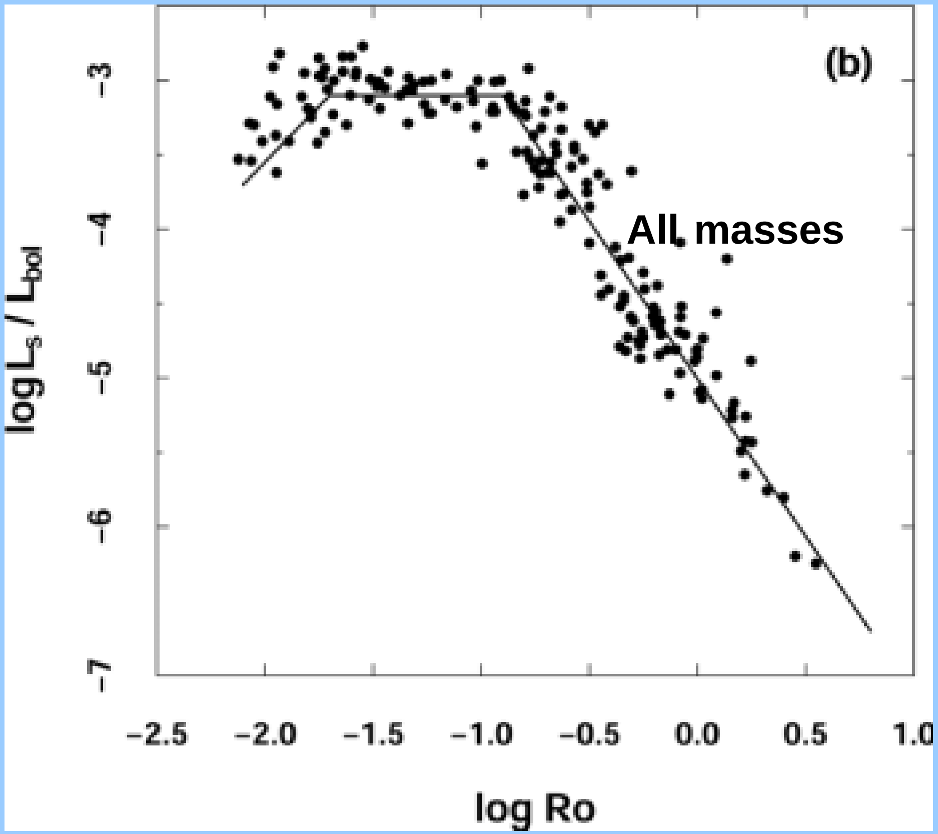
Very close double

Stellar magnetic activity and rotation

Recall for main sequence stars….

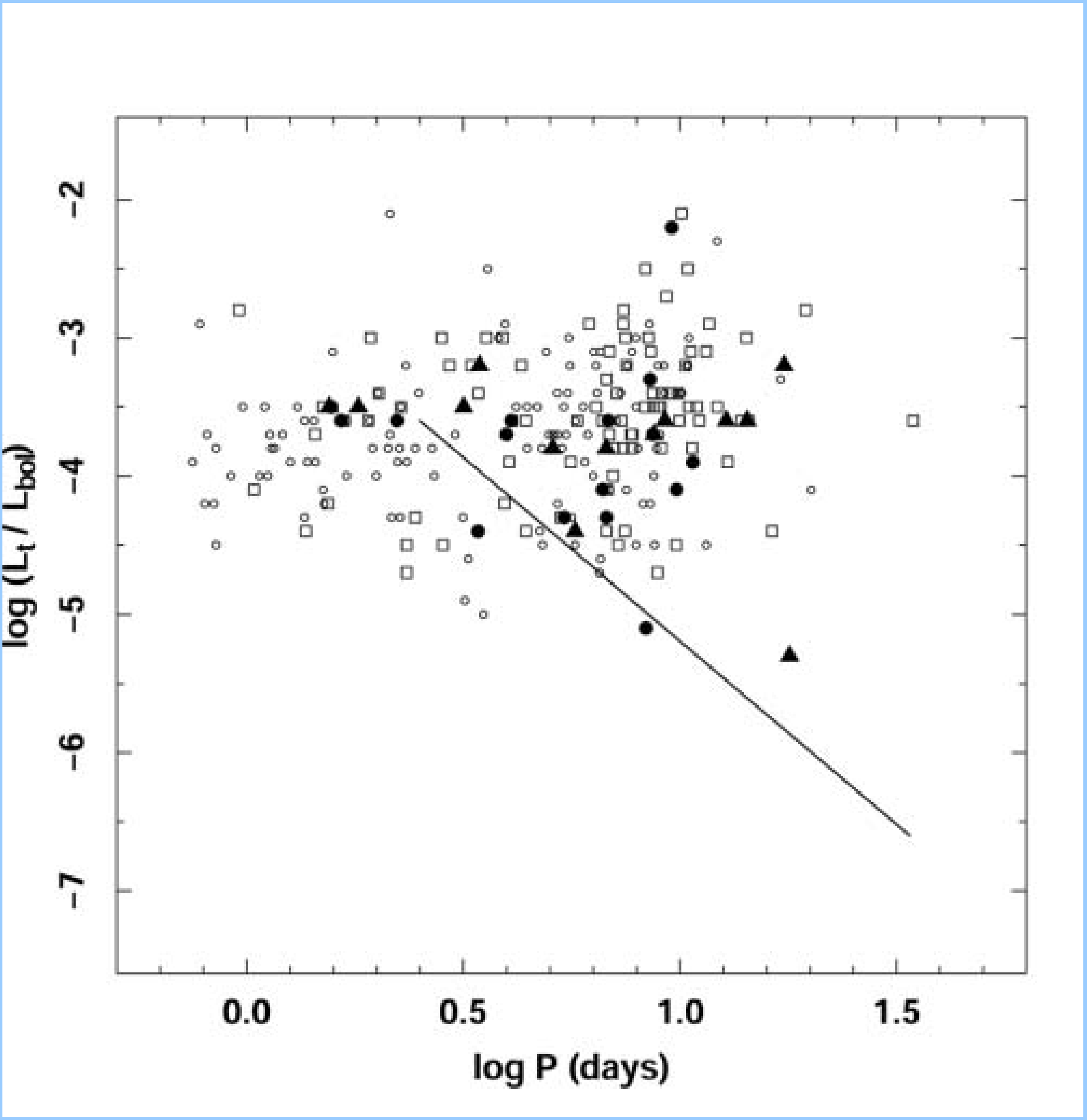


Gudel et al. 1997



Randich 2000

Magnetic activity is principally correlated with rotation consistent with solar dynamo theory

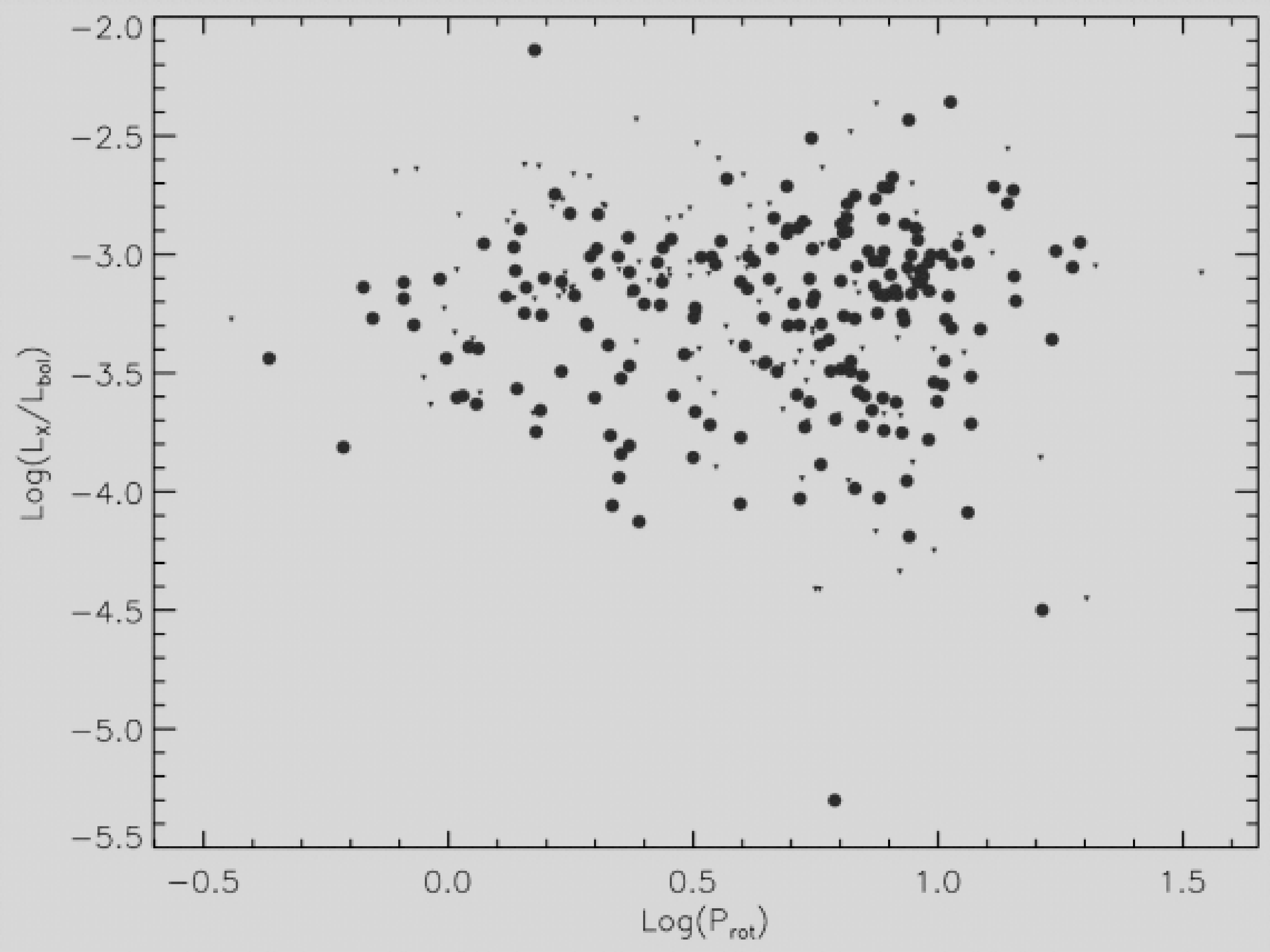


For 232 ONC stars with $M<1.5\ M_8$ …

… the activity-rotation relation is absent!

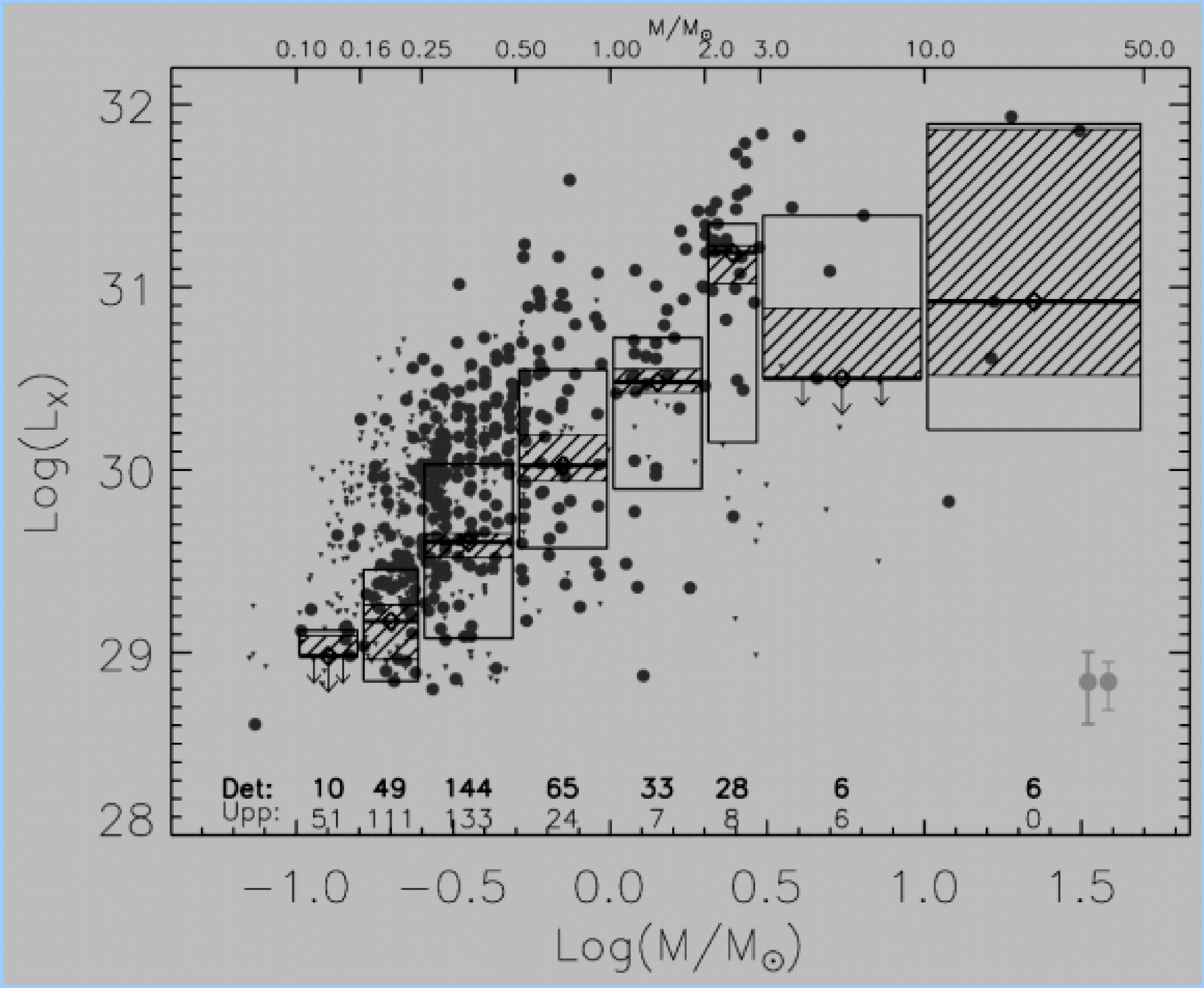
Feigelson et al. 2003

Same result obtained with Chandra HRC study



Flaccomio et al. 2003

Principal correlates with L_x: Mass, L_{bol} and radius



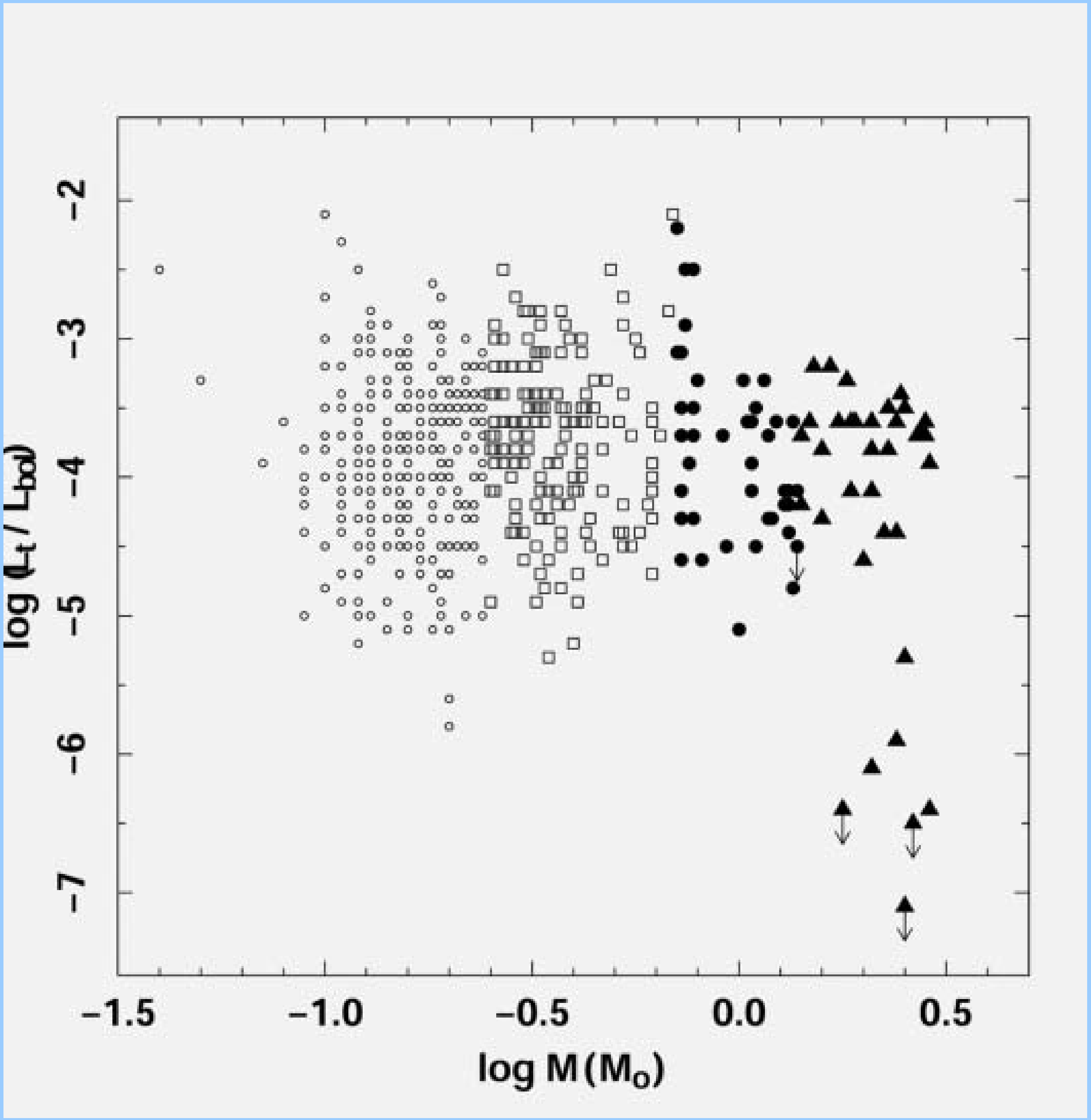
Flaccomio et al. 2003

Note 2-3 M_8 stars

with low L_x.

High L_x stars may

be binaries.



Feigelson et al. 2003

Dynamo interpretations

Standard ζ4T#dynamo

All PMS stars lie in the `supersaturated' regime?
How do we explain the L_x-L_{bol}-R-M relations?

Distributed turbulent dynamo

Recent MHD models of PMS turbulent convective dynamos roughly predict activity is independent of rotation, but more calculations to match correlations are needed.

(Rudiger, Kuker, Stix, Moss, Kitchatinov)

Change of X-ray behavior at M>2-3 Mo may reflect dynamo change from full convection to radiative core

High energy radiation from PMS stars will affect the circumstellar environment

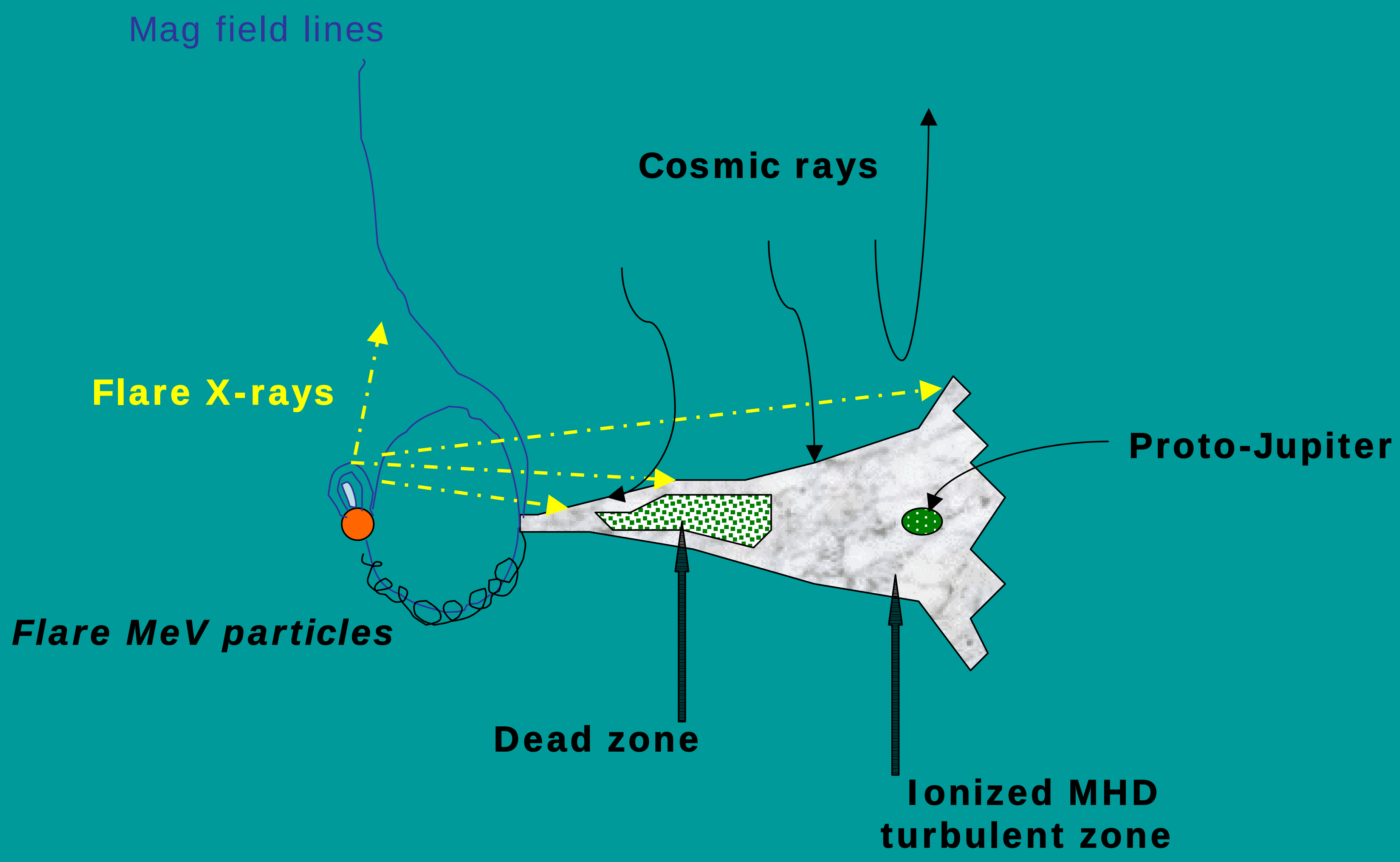
Soft X-rays will be absorbed within $\mathit{log}N_H$ ~ 21-23 cm^{-2} of the star. Each X-ray produces 10^1 molecular ions which are coupled to B fields and affect astrochemistry. These X-ray Dissociation Regions compete with Galactic cosmic rays in producing low level ionization in molecular clouds.

Reviews: Hollenbach & Tielens ARAA 1999, Glassgold et al PPIV 2000

On interstellar cloud scales, 0.01 < d < 10 pc, estimated integrated X-ray ionization may dominate CRs near young stellar clusters. But no spatial link between PMS stars and ions (e.g. HCO^+) yet seen.

Caselli & Walmsley 2001, Lorenzani & Palla 2001

High energy processes in young stellar objects



Possible X-ray effects on disks & planet formation

1. Ionize disk: active turbulent zone vs. dead zone.
   Jovian vs. terrestrial zones?

2. MHD turbulence promotes accretion & may inhibit planetary migration
   Hot vs. cold Jupiters?

3. Couple Keplerian orbits to magnetically collimated bipolar outflows

4. MeV flare particles bombard disk solids producing rare isotopes
   Meteoritic short-lived radionuclides?

4. X-ray flash from flares melts disk solids
   Meteoritic chondrule formation?

5. X-rays heat outer disk, change chemistry, melt ices
   IR disk properties (ISO, SIRTF)?

See Feigelson poster on Chandra & planet formation for details.

Conclusions

Much progress from UHURU to Chandra.

Rich imaging, spectral, temporal phenomenology in young stellar clusters.

Pre-main sequence stars exhibit a high level of high energy processes from magnetic reconnection with a bewildering variety of X-ray flares.

Activity is linked to L_{bol} and mass rather than rotation. Evidence for turbulent dynamos?

Flares affect the circumstellar environment, so X-ray studies address: disk turbulence & viscosity; origin of meteoritic isotopes & chondrules; disk heating & chemistry; Jovian planet formation & migration; disk longevity.